WATER AND SLURRY BULKHEADS IN UNDERGROUND COAL MINES: DESIGN, MONITORING, AND SAFETY CONCERNS

S. Harteis, NIOSH, Pittsburgh, PA
D. Dolinar, NIOSH, Pittsburgh, PA

Abstract

Many mining operations rely on bulkheads to provide a barrier between impounded water or slurry and active mine workings. However, bulkhead failures could cause and have caused catastrophic flooding that puts the underground workforce at risk. The National Institute for Occupational Safety and Health[1] (NIOSH) in collaboration with the Mine Safety and Health Administration (MSHA) is conducting research to evaluate the adequacy of existing design practices for water and slurry bulkheads. A key component of this research effort is documentation of the performance history and design parameters for bulkheads installed in underground coal mines during the last 20+ years. This research is part of a larger effort to develop general design guidelines and procedures for constructing and maintaining bulkheads that will help to ensure their long-term structural integrity, while significantly reducing the inundation risk for miners.

This paper presents the results of NIOSH's research to identify state-of-the-art bulkhead designs, including design criteria, leakage monitoring systems, and emergency warning systems. Underground observations and evaluations of existing bulkheads suggest that the most important design factors influencing their performance are the interface of the bulkhead with the surrounding strata and the potential magnitude of the hydraulic pressure to which they may be subjected. When a bulkhead has failed, leakage has generally been through the surrounding strata or along the bulkhead/strata interface, with the failure potential along the interface increasing with hydraulic head. It was also determined that development of a monitoring program to ensure the long term structural integrity of bulkheads is an important safety consideration. Current monitoring procedures range from weekly visual inspections to constant monitoring via pressure transducers and fluid level indicators. Where possible, these devices are used in conjunction with a computer based mine monitoring system to alert mine personnel when an emergency condition exists at the bulkhead installation.

Introduction

Underground mines install bulkheads across openings for a variety of purposes (Table 1). Bulkheads are most commonly used as a dam to contain water or liquid-like mine wastes (tailings or slurry) in abandoned mine workings (Figure 1). Bulkheads are also used as regulators to restrict the flow of water from abandoned mine workings into active mining operations. In some cases where abandoned mine workings are located beneath a refuse impoundment, bulkheads are installed at the surface entrances to the abandoned mine workings to prevent the outflow of water and liquid-like mine wastes from the openings if the overlying refuse impoundment should break through into the abandoned mine workings. Failure of any of these bulkheads could result in a disastrous inundation, with the potential for significant loss of life or property, and possible damage to the environment.

While no mining fatalities have been directly attributable to bulkhead failures, recent catastrophic mine inundations have underscored the need for sound engineering practices for the design and maintenance of these structures to decrease the potential for loss of life. On March 1, 1991, bulkheads designed and constructed to impound water were installed across the main entries between the abandoned Raccoon No. 3 Mine and the down-dip and active Meigs No. 31 Mine. On July 11, 1993, an inundation occurred at Meigs No. 31 Mine when these bulkheads failed. Fortunately, early discovery of the failure and a sufficiently slow water flow enabled all miners to escape from the Meigs No. 31 Mine. A subsequent investigation by MSHA (Tulanowski et al., 1993) indicated that the likely failure mechanism was erosion (or piping) along the concrete/fireclay interface at the base of the bulkhead.

Table 1. Functional types of bulkheads installed in underground coal mines.

MSHA District	Number of Bulkhead Sites	Water Storage	Refuse Disposal Related	Slurry Injection	Mine Fire	Permitted Not Built	Permit Review
1	0						
2	7	5			2		
3	4	3			1		
4	8	3	3				2
5	3	1				2	
6	3		3				
7	0						
8	1					1	
9	1	1					
10	4	2		2			
11	3	2		1			
TOTAL	**34**	**17**	**6**	**3**	**3**	**3**	**2**

In 2002, Congress requested that the National Research Council investigate the October 11, 2000 failure of the Martin County Coal Corporation impoundment near Inez, KY. In this incident, over 250 million gallons of impounded slurry broke through a bulkhead, flowed through an underground mine, and ultimately discharged into nearby creeks and streams, causing significant environmental damage. Fortunately, the incident caused no injuries or fatalities. Wu, Owens and Fredland (2003) noted that several other breakthroughs of slurry into underground mine workings similar to this incident have occurred in recent years.

Prior to construction of any bulkhead, the Mine Safety and Health Administration (MSHA), and possibly state agencies, must review and approve the design. This usually entails submission of a proposed design by a registered professional engineer for evaluation by the MSHA Technical Support Group. However, comprehensive engineering guidelines for the construction of reliable underground bulkheads do not currently exist, which makes it difficult for mine operators to design bulkhead installations. State and federal agencies have also expressed a need for design guidelines to assist in their permit review and approval process.

Existing and proposed bulkhead installations

To understand the requirements for bulkhead installations and the permitting process, NIOSH researchers examined the bulkhead permits submitted to the MSHA Technical Support office in Bruceton, PA. Researchers then visited MSHA district offices, state mining agencies, and contacted engineering consulting firms to document submitted permitting information and to determine the number of

[1] Disclaimer: The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

installed bulkheads and their locations in U.S. coal fields. Once this information was tabulated, accessible bulkheads at underground mining operations were visited (Figure 2) to gather information on monitoring methods and procedures, emergency response plans, construction practices, and maintenance issues. A total of 34 bulkhead sites (existing or in the permit stage) were identified in the 11 MSHA Districts (Table 1).

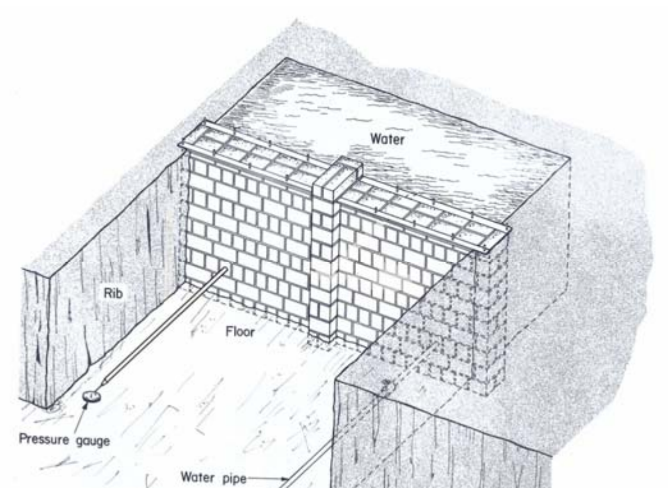

Figure 1. A concrete bulkhead installation with a pass-through pipe and a pressure monitoring device (Checkan, 1985)

Figure 2. Researcher examining a bulkhead installation in an underground coal mine.

Of the 34 bulkhead permit applications reviewed, 17 were constructed to create an active water reservoir or control water flow from abandoned mines (Table 1). These installations rely on pumps to maintain the impounded water at a safe level, or drain pipes that regulate the flow of water out of an abandoned area. At one operation, the mine manager stated that the active mine has been idled during times of high water flow, but the bulkheads sufficiently regulated the flow to prevent inundation of the active works.

Six bulkhead installation sites were used for refuse disposal. Two were installed across abandoned mine openings in the footprint of a surface impoundment to allow disposal of mine refuse to an elevation above the mine workings and prevent water or slurry from entering inactive mine works (U.S. Department of Labor, 2003). The remaining four bulkheads were constructed as a secondary line of defense in the event of an unexpected inrush of water or slurry into the mines from impoundments located on the surface above the abandoned mine works.

Of the remaining 11 installations, three bulkheads were constructed to seal off an underground area for slurry injection. Three were built to contain water to inundate an area of the mine in an attempt to extinguish a mine fire. Permits were issued for bulkheads at three sites, as of this writing, have not been constructed, and the remaining two sites are in the permitting stage.

Permitting process

Guidelines do not currently exist for preparing an MSHA or State permit application for a bulkhead installation. As a result, bulkhead permit applications that do not contain sufficient information are frequently submitted to federal and state agencies for approval. When the application is received in the MSHA district office, it is forwarded to the Technical Support Group located in Pittsburgh, PA for their review and comments. The Technical Support Group reviews the submitted information and develops a list of comments and recommendations for additional items to be addressed. The MSHA district office then forwards the list of comments and recommendations to the permit applicant. Once the applicant receives MSHA's comments, they submit a response to the MSHA district office. The response is reviewed by the MSHA district office and may be returned to the Technical Support Group for any additional review and comment. This procedure is repeated until MSHA is satisfied that all aspects of the bulkhead installation are adequately addressed.

In an attempt to improve the engineering content and expedite the permitting process, NIOSH developed the following summary of information that is generally required by MSHA for permitting a bulkhead installation. It is not intended to be an all encompassing list, but it can be a guide to assist the permit applicant in designing a safe and efficient bulkhead system. At some locations, state agencies follow a similar permit approval process. It is recommended that the permit applicant contact the appropriate state agency to explore specific permitting requirements.

Basic permit requirements

A bulkhead installation permit may be treated as a part of the mine ventilation plan, refuse disposal plan, abandonment plan, or an independent plan. Before the actual bulkhead permit is developed, a joint meeting should be held with representatives of MSHA, the appropriate state agency, and the permit applicant to discuss the bulkhead installation and permitting requirements. This will give the applicant a chance to explain the need for bulkheads and the anticipated operating parameters. The permit review procedure should be discussed to determine what information is required, and establish points of contact for each party involved in the permitting and construction of the bulkhead. Maintaining open lines of communication can play a key role in timely approval. In addition to the information discussed in the following sections, the general items listed below will be required in the permit package:

- Mine map showing the proposed location of the bulkheads. This map should contain the mine floor elevation contour lines and indicate the extent of the expected water pool.
- Mine map showing the expected water flow path(s) if a bulkhead should fail, and areas where water may discharge, and perhaps accumulate, on the surface, if applicable.
- Written discussion of why bulkheads are needed and how the lack of these structures will adversely impact the mining operation.
- Written procedures to maintain the proposed water or slurry elevation of the underground impoundment.
- Chemical analysis of the water or slurry to be impounded.
- Map of any adjacent, overlying, and underlying mine workings, active and inactive.
- Map of surface features such as ponds, lakes, streams, rivers, impoundments, and any other sources of water that could impact the integrity of the bulkhead.
- Discussion of potential consequences if bulkhead system fails and a plan of action to mitigate such consequences.

Geotechnical considerations

The mine layout will determine the location for the bulkhead.

Therefore, geotechnical information on the site-specific conditions is required, especially considering that most known bulkhead failures have been through the surrounding strata or along the strata/bulkhead interface. Geotechnical factors that should be addressed include the geology, hydrology, and ground control issues.

The geologic characteristics and conditions for the site where the bulkhead will be constructed need to be identified and evaluated. The strata in the immediate roof, floor and ribs should be described in detail to include all strata that could be affected by a change in hydrologic conditions or the bulkhead installation. Since, in many cases, the immediate floor or roof consists of an underclay, fireclay or other weak material that may degrade when exposed to water, a site evaluation must be done to a depth where competent strata is identified that will not be affected by water. Data on the strata strength and effects of water exposure should be included to indicate the strata competency. Any conditions associated with the mined coalbed such as clay or rock partings, or cleat properties that could be adversely affected by exposure to water and thus become a conduit for water flow around the bulkhead must be identified.

From a ground control standpoint, there are both general area and site-specific stability issues that should be addressed. The stability of the pillars in the general area of the bulkhead installation should be evaluated. Coal pillars, to which bulkheads will be anchored, as well as adjacent pillars, must remain stable for the life of the impoundment. Engineering calculations that demonstrate a sufficient safety factor for long term stability of these pillars should be included. If future mining adjacent to the underground impoundment is planned, documentation showing the effects of this proposed mining on the stability of the impoundment should be submitted. This should include information on the stability of the barrier pillar and development pillars.

The stability of the site-specific openings where the bulkhead is to be placed should also be addressed. The bulkhead should be constructed where competent roof and floor strata exist. Every effort should be made to avoid placing a bulkhead near pillar corners where the rib, roof, and floor strata commonly exhibit increased fracturing. Any potentially adverse ground control conditions such as roof falls, pillar punching, floor heave, pillar bursts, or other unusual conditions in the entry area where the bulkheads are to be installed, should be evaluated. The permit package should include details of existing roof support practices and planned additional roof support to protect the bulkhead structure, both inby and outby. Soft floor material should be removed before installing posts or cribbing for roof support. Supports inby the bulkhead will be exposed to water or slurry and should be designed accordingly. Since long term monitoring of the bulkheads will be required, additional roof and rib support should be considered along the travel ways that will be used for inspection purposes.

When it has been determined that the strata surrounding the bulkhead has the potential for leakage with long term exposure to water, the steps necessary to mitigate this condition should be addressed in the permit package. If the mine floor or roof is prone to erosion or degrades significantly when exposed to water, it must be removed from the footprint of the bulkhead, so that it can be constructed on hard, competent rock. In some operations, there is a potential for coal pillars located inside the impoundment area pushing through the saturated floor strata. If this condition exists, its effect on the stability and safety of the impoundment, along with any proposed engineering solutions, should be addressed.

Because the strata surrounding the bulkhead may contain fractures that could allow water to leak around the bulkhead, the need for sealing the strata and associated fractures should also be evaluated. This sealing process could include the drilling of holes into the strata and pumping grout into the fractures. Further, consideration should be given to sealing any water sensitive strata that can not be removed for a sufficient distance around the bulkhead to minimize leakage and prevent large volumes of water from flowing into the underground workplace. Essentially, measures may need to be taken to increase the length of any potential water flow paths through the strata and around the bulkhead. To what degree the surrounding strata and fractures may have to be sealed will depend on the expected water head behind the bulkheads and the bulkhead design. Due to the strata conditions and the potential for excessive leakage through the strata, grout injection into the surrounding strata was either performed or planned for nearly two thirds of the bulkheads that were installed or permitted.

If the impoundment area is adjacent to mine workings, documentation should be provided to demonstrate that the barrier separating the impoundment from the adjacent works will remain stable and will not rupture, thus preventing water or slurry from breaking into the adjacent works or seeping through the coalbed and surrounding strata. Similar documentation should be submitted if the impoundment is adjacent to the coalbed outcrop.

Bulkhead Structure

Table 2 gives a breakdown of the bulkhead designs currently in use at U.S. mine sites. The primary designs for underground use are tapered plugs, parallel plugs, notched slabs, or variations of these basic designs (Figure 3). Bulkheads installed at mine entrances on the surface to prevent water from entering a mine may utilize a reinforced concrete structure built in front of the mine opening to “cap” off the opening (Figure 4), or pneumatically stowed crushed limestone in the entry between two concrete block walls with injected grout or polyurethane into the crushed limestone to form a water tight seal (Figure 5). The design that best suits the site-specific application will depend on anticipated water or slurry load (head pressure), accessibility to the site from underground as well as surface, rib, roof, and floor conditions, floor heave, convergence, material handing restraints, cost, and several other variables.

Table 2. Types of bulkhead designs used in underground coal mines.

MSHA District	Number of Bulkhead Sites	Parallel Plug	Tapered Plug	Notched Slab	Grouted Rock	Cap
1	0					
2	7	1		6		
3	4	3		1		
4	6		2	2	1	1
5	3			3		
6	3	1		1		1
7	0					
8	1			1		
9	1		1			
10	4	1		3		
11	3	2		1		
TOTAL	**32**	**8**	**3**	**18**	**1**	**2**

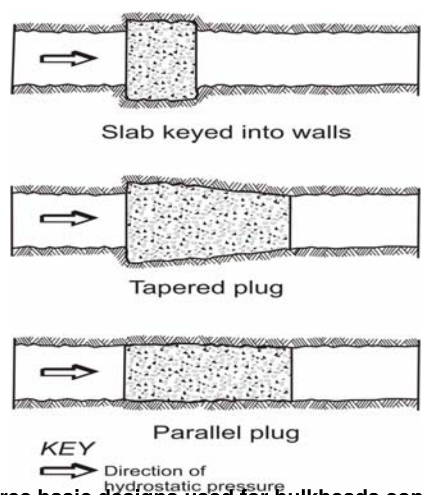

Figure 3. Three basic designs used for bulkheads constructed in underground coal mines (Garett and Campbell Pitt, 1958).

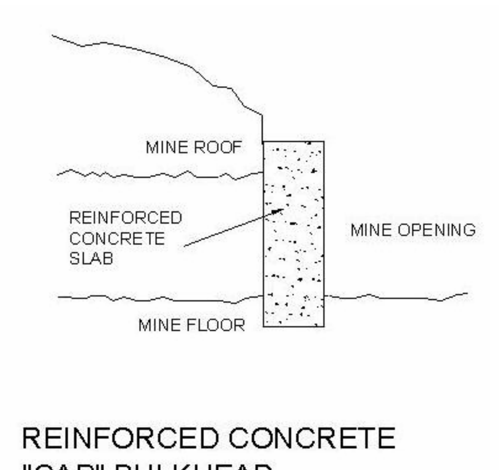

Figure 4. Reinforced concrete "Cap" bulkhead installed across drift opening to contain an unexpected inrush of water or slurry from surface impoundment above the abandoned mine works.

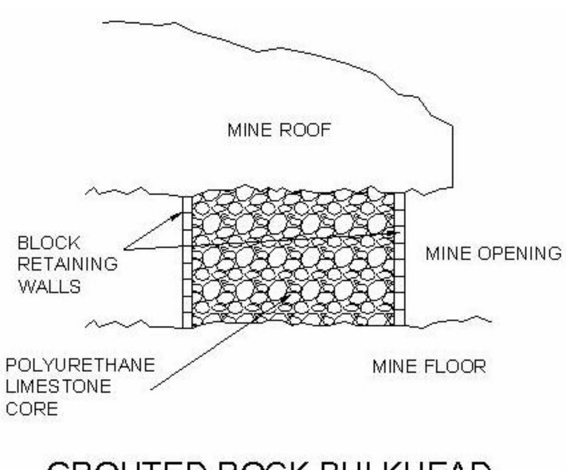

Figure 5. Grouted rock bulkhead installed across drift opening

A wide range of construction materials have been used in bulkheads, as given in Table 3. The selection of a construction material depends on the bulkhead design selected, accessibility to the installation site, and cost.

The bulkhead structure must be designed to withstand the expected maximum head pressure with an appropriate margin of safety. To determine the maximum head pressure, the engineer must consider not only the water or slurry to be stored in the impoundment behind the bulkhead, but also potential additional sources of water such as groundwater or water in adjacent mines, operating or abandoned, in overlying or underlying coalbeds. One of the operations visited by NIOSH's researchers had experienced an increase in water discharge when pumps were removed from service and the water level in an abandoned underlying coal mine then rose above the elevation of the active mine.

Sources of surface water such as slurry impoundments, rivers or streams that could find their way into the underground impoundment must also be considered when calculating the potential head pressure acting upon a proposed bulkhead. Once the maximum design pressure is established, the normal operating pressure should be calculated based on the usual inflow rate and the rate at which water will be removed from the impoundment area. Some operations rely on surface or deep well pumps to remove water and maintain a normal operating pressure on the bulkheads, while others utilize pumping stations located underground. One installation evaluated by NIOSH was designed to allow mine water to build up against the bulkhead until it discharged from an existing portal by natural flow, thus limiting the normal operating pressure. Regardless of the method used, details must be provided in the permit application addressing how the normal water or slurry level will be maintained.

Table 3. Types of materials used to construct bulkheads.

MSHA District	Concrete	Cementitious Foam	Polyurethane Limestone	Polyurethane	Masonry	Shotcrete
1						
2	4		1	1	1	
3	2		1	1		
4	2	2	1			1
5	1		2			
6	2		1			
7						
8			1			
9	1					
10	1		3			
11	2	1				
TOTAL	**15**	**3**	**10**	**2**	**1**	**1**

Structural calculations are required in the permit applications to show that the proposed bulkhead design will withstand the maximum expected head pressure. This section of the permit application must include the types of construction materials to be used, strength values for the surrounding strata and the source of this information, bulkhead construction material properties and characteristics, including those of any reinforcement steel. The calculations should be performed under the supervision of a registered professional engineer that has experience in the design and installation of water retention structures, and who is also familiar with underground mining. The specific calculations required will depend on the type of bulkhead structure, and will not be covered in this report. However, adequate safety factors must be used in all bulkhead designs due to unknown conditions that could exist in the mine roof and floor, and the mine safety consequences associated with a potential failure.

Other design parameters to consider:

- Steel reinforcement placed inside the bulkhead structure should be coated to prevent corrosion.
- Cement-based products proposed to construct bulkheads in large pours will require a detailed plan to reduce the heat of hydration to avoid expansion/contraction as a consequence of heating.
- Selected construction materials must be compatible with the quality of water or slurry stored, specifically, they must be resistant to deterioration by acid mine water.
- It is normal for bulkheads to contain pipes that pass through the structure to monitor pressures on the bulkhead and to release water in emergency situations (Kirkwood and Wu, 1995). Pipes installed to reduce the water level should contain a U-trap on the downstream end and means to prevent clogging of the pipe on the upstream end. The pressure monitoring pipe should include a visual pressure gauge and shut-off valve. This pipe should also be protected from clogging. These pipes should be equipped with anti-seep or external collars to reduce leakage along the interface of the pipe and bulkhead structure. All pipes should be coated for corrosion protection.
- If the bulkhead is located in a seismically active area, the design should consider what effect the dynamic and hydrodynamic forces that result from an earthquake will have on the bulkhead structure.

Detailed bulkhead construction procedures should be listed in the permit application. Information should include: site preparation requirements, procedure for roof, floor, and rib hitching, thickness of material lifts, if applicable, and procedures to seal the interface between the bulkhead and the surrounding strata. Quality control procedures should also be included to address how and what construction materials will be sampled for testing. This includes sampling rate, sampling procedure, required laboratory testing, required results, and measures to be taken if test results indicate substandard material.

Monitoring

The permit application should include provisions for competent person to monitor the construction of the bulkhead. The duties of this person should include, but not limited to: maintain a daily log of construction activities, monitor construction progress to assure compliance with the approved plan, ensure sampling of construction material, and document any variance(s) from the approved plan.

Once the bulkhead is constructed, it will require routine monitoring of key performance parameters. At a minimum, the date, time, pressures, leakage rates, and visual observations should be recorded and maintained in the mine office. The frequency of the inspections will depend on the location of the bulkhead, head pressure, location of active works with respect to the impoundment, and other operating conditions. Normally, these inspections become part of the regularly required airway examinations. The permit application should include a list of the information to be recorded during the inspection and the proposed inspection frequency.

The head pressure against the bulkhead should be monitored using a pressure gauge with a visual indicator connected to a pipe passing through the bulkhead structure. The permit application should include details of how the pipe will be installed and what measures will be taken to prevent the pipe from plugging. When possible, mine operators should connect bulkhead pressure transducers to their existing mine monitoring system. This allows for constant monitoring, and provides a record of the bulkhead pressure changes over time. An added benefit is the ability to preset threshold pressure levels that, when exceeded, will cause the system to send an alarm to the mine office. If a mine-wide monitoring system is not in place, commercial stand-alone data gathering systems are available for monitoring bulkhead pressures. Regardless of the system chosen, the permit will need to state what system is being used, where the information will be monitored, and how the information is being stored and maintained for future reference. Consideration should also be given to including a back-up system independent of the primary system to monitor water pressures against a bulkhead. One option is to utilize a surface borehole equipped with a piezometer to measure the water depth in the mine impoundment. Once the pool elevation is determined, one can calculate the resultant pressure on the bulkhead.

Minor leakage through the strata adjacent to bulkhead systems is not abnormal, especially if the hydrostatic head is high. Plans to monitor the bulkhead system leakage rate should be included. Once the bulkhead is in place, this information will be valuable in determining what areas need additional grouting and can also be a measure of bulkhead or adjacent strata degradation over time. Some operators construct a low threshold dam in front of (outby) the bulkhead to capture the leakage and pass it through a v-notch weir. The height of water above the apex of the v-notch can be used to calculate the leakage rate. Other operators construct a similar dam to capture the leakage and gravity feed it into a pipe that discharges into an existing sump. The leakage rate can be determined by filling a graduated cylinder directly from the pipe and recording the time required to fill the cylinder. The leakage rate is recorded during each routine examination along with the bulkhead pressure. The data is recorded on a chart in the mine office that shows leakage rate and bulkhead pressure versus time.

Emergency planning and training

An emergency response and evacuation plan should be developed and included in the permit application package. The plan would include a list of events that would trigger an emergency response, what actions are to be taken, and who is responsible for coordinating these actions. The triggering event could be a sudden increase in pressure at the bulkhead, deterioration of the bulkhead structure or surrounding strata, increased leakage, or other indications that the bulkhead system could be in jeopardy. Actions could include more frequent bulkhead inspections, reducing the water or slurry elevation in the impoundment to an acceptable level given the developing conditions/problem, removal of employees from areas that could be inundated if a bulkhead fails, or complete evacuation of the mine.

The emergency plan should include maps with the potential inundation area delineated, emergency exit routes, location of emergency supplies, access to communication, and designated meeting locations. If part of the emergency plan is to drain water through the bulkheads, a map should be included indicating the water flow path and location of areas that will pool water. When establishing exit routes, pay close attention to mine floor elevations. Existing primary and secondary escapeways may become impassable during a bulkhead failure, and air courses could flood and change ventilation patterns.

Training is the cornerstone of an effective emergency plan and should be included in the permit package. All employees exposed to a bulkhead system should be familiar with the installation and receive training on procedures to follow if an inundation or failure occurs. At a minimum, annual re-training should be conducted with each employee and all workers should be made aware when changes occur in the emergency escape routes or procedures.

Summary

Designing and permitting an underground bulkhead system is not a simple task. Engineering design considerations for the bulkhead structure must include its interaction with the surrounding strata, and how it will impact the underground operations and most importantly, the potential risk to the underground workforce. The bulkheads should be designed by a registered professional engineer who has significant experience in the design and installation of water retention structures and is familiar with underground mining. A detailed plan for the bulkhead installation should be developed and the actual installation closely monitored.

Acknowledgements

The authors acknowledge the assistance of Terence M. Taylor, Senior Civil Engineer of MSHA's Mine Waste and Geotechnical Engineering Division in providing information on existing and planned bulkhead permits.

References

1. Checkan, Gregory J. (1985), "Design of Bulkheads for Controlling Water in Underground Mines", U.S. Bureau of Mines Information Circular 9020.
2. Garrett, W.S., and Campbell Pitt, L.T. (1958), "Tests on an Experimental Underground Bulkhead for High Pressures", J. S. African Institute of Mining and Metallurgy, pp 123-143.
3. Kirkwood, Donald T. and Wu, Kelvin K. (1995), "Technical Considerations for the Design and Construction of Mine Seals to Withstand Hydraulic Heads in Underground Mines", Paper presented at SME Annual Meeting, Denver, CO, Preprint No. 95-100.
4. Tulanowski, Ronald T., Kirkwood, Donald T., and Gardner, George H. (1993), "Non-Injury Water Inundation, Meigs No. 31 Mine", U.S. Department of Labor Accident Investigation Report.
5. U.S. Department of Labor (2003), "Report to Congress: Responses to Recommendations in the National Research Council's Report Coal Waste Impoundments: Risks, Responses, and Alternatives", pp. 37-46.
6. Wu, Kelvin K., Owens, Harold L., and Fredland, John W. (2003), "MSHA's Review of Impoundment Plans", Paper presented at SME Annual Meeting, Cincinnati, OH, Preprint No. 03-099, p.10.